Generating Cosmological Magnetic Fields

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Durrive & Aubert, 2017, in prep

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• Magnetic fields **everywhere**: from stars to galaxies to cosmic voids

![Diagram showing magnetic field scales](image)

Generally:

- Small scale
- Large scale
- Strong field
- Weak field

• **Cosmological** Magnetic fields:

  **Observational upper bounds:**
  - CMB: $B < 5 \text{ nG (comoving)}$ at 1 Mpc *(Planck results 2015: XIX)*
  - Constraints from structure formation $B < nG$ at protogalactic scales *(Wasserman 1978, Kim et al 1996)*

  **Observational lower bounds:**
  - High energy gamma rays (Fermi and HESS): $B > 10^{-16}$ or $10^{-18} \text{ G (?)}$ in a significant fraction of the IGM *(Neronov&Vovk 2010, Taylor et al 2011, Takahashi et al 2011, ...)*

**Origin(s)?**

• Current paradigm:
  1) Generate **weak seeds**
  2) **Amplified**: compression during structure formation (flux freezing) + dynamos

• Turbulence in structures → B fields lost their initial properties → look at the **Intergalactic medium** where seeds did not evolve too much
• Current status of amplification process studies:

\[ \rightarrow \text{we need } \sim 10^{-22} \text{ to } 10^{-12} \text{ G seeds} \]

• Numerous mechanisms:
(Reviews see e.g. Ryu et al 2012, Widrow et al 2012, Durrer & Neronov 2013, ...)

I) Primordial Universe mechanisms

• **Inflation:** quantum fluctuations of electromagnetic field, but need non-standard electromagnetism
• **Phase transitions:** electroweak and quark-hadron
• **Recombination:** rotating plasma blobs interacting with background radiation

II) Post recombination mechanisms

• **Thermal (Biermann) battery:** in stars, from cosmological shocks during cosmic web formation, from propagating ionization fronts at EoR in large structures
• **Plasma instabilities:** many, but e.g. Weibel instability
• **Radiation:** Thomson scattering In protogalaxies, **Photoionization** at EoR in the IGM or around first stars
• **Outflows:** Galactic winds from galaxies in clusters, from void galaxies, AGN outflows
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**No preferred mechanism so far. Fields not strong enough on intergalactic scales**
Astrophysical mechanism generating intergalactic magnetic fields at the Epoch of Reionization

Neutral → Ionized

Recombination
(380,000 years)

Epoch of Reionization
(1 billion years)

Today
(14 billion years)

Strömgren sphere
Intergalactic medium (Hydrogen)

Strömgren sphere (HII region)

Source
\[ \lambda_{mfp} \propto \nu^3 \]

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Charge separation by photoionization

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Source
\( \nabla \times \vec{E} = 0 \)

Intergalactic medium (Hydrogen)

Strömgren sphere (HII region)

Source
Maxwell-Faraday equation: \[ \partial_t \vec{B} = -c \vec{\nabla} \times \vec{E} \]

→ Need **rotational \( E \) field** to generate \( B \)

**Inhomogeneities** of Intergalactic medium enable this

(Langer et al 2005)
\[ \nabla \times \vec{E} \neq 0 \]

Intergalactic medium (Hydrogen)

Strömgren sphere (HII region)

Source
Intergalactic medium (Hydrogen)

Strömgren sphere (HII region)

Source
Intergalactic medium (Hydrogen)

Anisotropic HII region

Source
\[ \nabla \times \vec{E} \neq \vec{0} \]

Intergalactic medium (Hydrogen)

Anisotropic HII region

Source
Formally

(Burrive & Langer, 2015, MNRAS)

Photoionization = local modification of the number of electrons and of their **velocity distribution**

⇒ Kinetic theory!
Source term in Boltzmann equation of electron distribution function:

\[
\frac{df}{dt} = \partial_t f \big|_{\text{photoionization}}
\]

Momentum transferred from photons to electrons:

\[
m_e \ddot{v} = f_{mt}(\nu) \frac{h\nu}{c} \hat{r}
\]

Fraction of momentum transferred

Induction equation:

\[
\partial_t \vec{B} = -\frac{c}{e} \frac{\vec{\nabla} n_e \times \vec{\nabla} p_e}{n_e^2} - \frac{c}{e} \vec{\nabla} \times \left[ \frac{\vec{p}_e}{n_e} \right]
\]

**Photoionization:**
Radiation induces magnetic fields!

Momentum transfer rate

Biermann
Resulting magnetic field

(Durrive & Langer, 2015, MNRAS)

Source of $B$:
Anisotropy of the column density

$$\vec{B}(t, \vec{r}) = \frac{N}{e x_e} \nabla \int_{r_s}^{r} n_{HI} dr \times \hat{r}$$

where

$$N = \frac{1}{4\pi r^2} \int_{\nu_0}^{\infty} f_{mt} \sigma^2_{\nu} L_{\nu} e^{-\tau_{\nu}} d\nu$$

Absorption along photon path

Cross section

Geometric dilution

Source spectrum

Ionizing photons

Fraction of momentum transferred
Resulting magnetic field

(Durrive & Langer, 2015, MNRAS)

Source of $B$:
Anisotropy of the column density

Inhomogeneity

$$\vec{B}(t, \vec{r}) = t \frac{N}{e x_e} \nabla \int_{r_s}^r n_{HI} \, dr \times \hat{r}$$

Numerical Approach:
collaboration with D. Aubert

Inhomogeneity

Strömgren radius

Cross section

Absorption along photon path

Geometric dilution

Ionizing photons

Source spectrum

Fraction of momentum transferred

where

$$N = \frac{1}{4\pi r^2} \int_{\nu_0}^{\infty} f_{mt} \sigma_\nu^2 L_\nu e^{-T_\nu} \, d\nu$$
Typical spatial distributions and scales

(Durrive & Langer, 2015, MNRAS)

- Gaussian inhomogeneities → analytical expressions
- Explicit lengthscales & magnetized regions
- Studied properties for various sources at various epochs:

Compared with intersource distances:

- Magnetization of the whole intergalactic medium

### Pop III clusters
- Strömgren sphere
- 2 kpc inhomogeneity

### First galaxies
- 20 kpc
- -19

### Quasars
- 2 Mpc
- -21
- -23

Best compromise power/dilution

- Compared with intersource distances:
  - magnetization of the whole intergalactic medium
Global magnetization level of the Universe

Case of galaxies:

Distribution of sources & clouds:
Given by underlying **Dark Matter halos**
(Press-Schechter formalism)

Mean magnetic field in the Universe:

Universe with *strongly ionizing* galaxies
(maximal escape fraction & stars formed to stay consistent with Planck)

Universe with *weakly ionizing* galaxies
(minimal escape fraction & stars formed to stay consistent with Planck)
Numerical approach

(Durrive & Aubert, 2017, in prep)

Generated B field with realistic profiles from cosmological simulations:

(example of a primordial galaxy at $z = 10$)

Ongoing work!
Evolution in the cosmic web?

B field generated early

→ Need to study the evolution of cosmological magnetic fields
Cosmological evolution of B in the cosmic web?

- Within intergalactic filaments

Vazza et al. 2014

Cosmic web at $z = 0$
Cosmological evolution of B in the cosmic web?

- Within intergalactic filaments

Vazza et al. 2014

Detectability & measurements?
Square Kilometre Array

- Galaxy evolution, cosmology and dark energy
- Strong-field test of gravity using pulsars and black holes
- The origin and evolution of cosmic magnetism
- Probing the Cosmic Dawn
- The cradle of life
- Exploration of the unknown
Square Kilometre Array

Phase 1 : construction 2018 – 2023
→ SKA1 : 10 % total surface, sc. op. 2020

Phase 2 : design 2018 – 2023, construction 2023 – 2030
→ SKA2

SKA1 mid
• Array on ~150 km in diameter
• 350 MHz – 14 GHz
• 197 dishes: 15 m & 13.5 m (64 MeerKAT)
• Pulsars, 21cm local univ., **galactic B & IGM**,…

SKA1 low
• Array on ~ 40 km in diameter
• 50 MHz – 350 MHz
• 131 000 double-polarization (+ ASKAP)
• Reionization, **galactic B & IGM**, exoplanets,…
Conclusion and discussion

- Astrophysical mechanism, operating for any source, **all along the EoR**
- Strengths comparable to Biermann battery, but on entire inter-source scales
  - ⇒ Contributes to **magnetization of the whole Intergalactic medium**
    interesting for voids!

- Specific spatial configuration:
  - may help discriminate the seeds from other mechanisms

- Directly measurable seeds ?
  - → $10^{-19}$ G fields prior and during EoR !
    (Venumadhav et al 2017, Gluscevic et al 2017)
Thank you for your attention